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Environmental Change and Tephra Deposition: the Strath of Kildonan, Northern Scotland

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Pollen analysis, tephra counts and geochemical data are presented from the upper 200 cm of a core from a basin mire in the Strath of Kildonan, northern Scotland. Three main tephra concentrations are located and tentatively dated to c. 7650 BP (Kl), c. 4250 BP (K2) and 3250 BP (K3) by cross correlation with the regional pollen chronology. The identity of the tephra layers is unknown but the peak at 4250 BP may be from the Hekla 4 eruption. The associated changes in catchment soils and vegetation are highly variable. Kl is associated with a major vegetation disturbance but no significant change occurs at K3. K2 is correlated with a large regional rise in pine pollen. These results conflict with previous studies on distal impacts of volcanic activity during the Holocene and demonstrate the diversity of environmental changes associated with Holocene volcanic activity.

Introduction

Much recent attention has been directed towards the discovery of Icelandic tephra layers in sediments in northern Britain (Dugmore, 1989; Dugmore & Newton, 1992; Bennett et al., 1992) and Ireland (Pilcher & Hall, 1992), and these have now been recorded in at least 30 locations (Hunt, 1993). The total number of events recorded is in some doubt but there may be at least nine separate Holocene events (Pilcher & Hall, 1992) which have deposited significant amounts of volcanic material in the northern British Isles. Once each tephra layer has been successfully characterized and identified, there is clearly enormous potential for the use of these features for more secure dating of environmental changes across this area (Blackford et al., 1992; Hall, Pilcher & McCormac, 1994). However, while tephra may be simply considered as a palaeoenvironmental research tool, it may also be an agent of environmental change itself. This paper studies the environmental impact, if any, of three Holocene tephra layers identified in a core retrieved from the Strath of Kildonan, northern Scotland.

Discussion of Holocene volcanic impacts on human populations and ecosystems in Britain has often implicated climate change as the primary forcing mechanism. Burgess (1989) has suggested that volcanically induced climatic deterioration in the late 2nd millennium BC may have caused the desertion of large areas of the uplands. Baillie & Munro (1988) have linked poor growth years in the Irish dendrochronology to volcanically induced acid peaks in ice cores and Baillie (1989) has suggested that climatic deterioration and/or consequent waterlogging is responsible for this. However, climate models and observations show that the degree of climatic change following even major eruptions is relatively minor and short lived (e.g. Bradley, 1988; Kelly & Sear, 1984; Mass & Portman, 1989). With the discovery of tephra fall in Britain, there has arisen the possibility that distant Icelandic eruptions, in particular the eruptions of Hekla known as H3 and H4, may have had a measurable direct effect on ecosystems and human populations here (Blackford et al., 1992; Grattan, 1994; Hall et al., 1994; Grattan & Gilbertson, 1994; Edwards et al., 1994) and even in the absence of particulate fall-out, acid aerosols have been shown to cause severe damage to a variety of plants in Britain and Europe in historic times (Thorarinsson, 1981; Grattan & Charman, 1994; Grattan & Pyatt, 1994). Indeed, it can be argued that acid deposition may cause a severe environmental change in vulnerable ecosystems (Bull, 1991) which is far in excess of that which might be expected from the minimal degree of climate change to be expected from either the H3 or H4 eruptions.

To date there have been few studies aimed directly

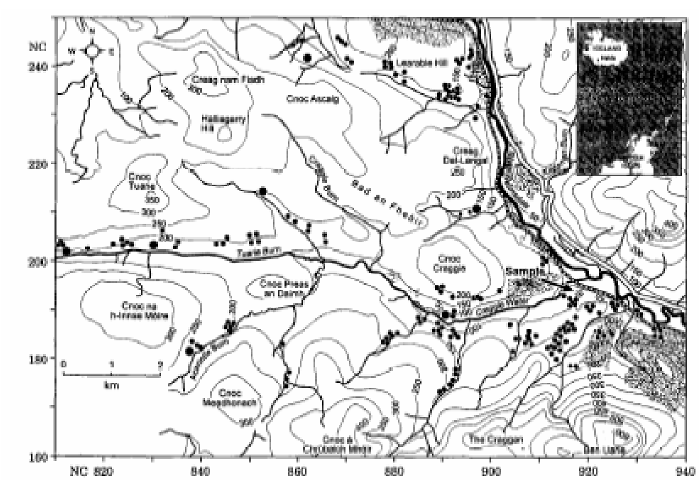

Figure 1. Location of the study site and relationship with surrounding archaeological features (chiefly Bronze Age hut circles). • = Individual sites; ● = cluster of sites.

at evaluating the impact of tephra fall on ecosystems and the results of such studies have been ambiguous. Blackford et al. (1992) demonstrate that the pine

decline in northern Scotland is coincident with a tephra fall from H4 and suggest that these events are causally related, while in contrast Hall et al. (1994) found no temporal link between the pine decline in northern Ireland and the H4 tephra layer. In mainland Europe, the Laacher See tephra has been studied in relation to environmental change but no significant impact can be detected in the vegetation record (Lotter & Birks, 1993). This study aims to examine a Holocene record of tephra fall in the Strath of Kildonan in north east Scotland, and to evaluate the impact of major events on soils and vegetation using sediment geochemistry and palynology.

The Study Site

The Strath of Kildonan lies along the border of Caithness and Sutherland, following the river Helmsdale (Figure 1). The strath was a major area of settlement in the 2nd millennium BC and over 2000 hut circles have been identified here (Lowe & Barber, 1988). In this respect it is similar to many other valleys in northern Scotland (Barclay, 1985) and like them, appears to have suffered major abandonment in the later part of the 2nd millennium BC (Burgess, 1985), leading to the theory that this was due to catastrophic environmental change resulting from a distant volcanic eruption (Burgess, 1989). The study of tephra horizons found in the Strath of Kildonan may therefore offer an opportunity to test this hypothesis as well as reaching an estimate of the timing, magnitude and impact of other Holocene volcanic events. The underlying geology is composed of relatively acid, base-poor rocks including granites, granulites, schists and some sedimentary rocks (Futty & Towers, 1982; Hudson, 1988) with a covering of Pleistocene drift deposits. The present climatic regime is classified as boreal, veriy humid (Birse, 1971). Rainfall is around 1200 mm yr - , winters are mild and summers are cool. The vegetation is primarily heather moorland and blanket mire with some rough grassland in the valley itself. There is a limited amount of open birch woodland in the valley of the Craggie water with some recent planted coniferous forest elsewhere in the Strath. The soils are dominated by a range of base deficient podsolic and peaty soils with deep organic peats in some places. The study site itself (NC91 7 194) is one such location (Figure l), where drainage has been impeded by a lateral moraine and approximately 5 m of sediment have accumulated in the basin. There is no evidence in this area for glacial activity during the Loch Lomond Stadial (Sissons, 1977) and the sediments should therefore cover the Devensian Lateglacial and the Holocene in their entirety. Several clusters of Bronze Age settlement were in close proximity to the sample site, particularly in the valley of the Craggie water to the west and on the lower slopes of Ben Uarie to the south (Figure 1).

Methods

The mire was probed to locate the deepest point and a 4.9 m core was retrieved using a 9 cm diameter Russian pattern peat corer. The stratigraphy was recorded and the core was sampled contiguously by scrapes at 10 cm intervals for tephra. Samples for pollen and geochemistry were also taken at 10 cm intervals. Further samples were taken for all these analyses at 1 cm intervals once the major tephra peaks were identified. Tephra was extracted by the following procedure. This method has the advantage of being simple and effective and does not involve the application of particularly volatile chemicals. However, it is only suitable for the extraction of tephra for counting as the reagents modify the alkaline geochemistry of the tephra.

Disaggregate 1 cm3 sample in warm 10% NaOH.
Leave overnight. Sieve (180 urn), wash through and decant supernatant.
Rinse with deionized water until water becomes clear.
Transfer to beakers with 50 ml 20 vols H,O, and mix well. Heat gently in water bath for 2 h (do not allow to boil). Remove from heat and leave overnight.
Transfer to centrifuge tube, wash, centrifuge and decant (x 4).
Transfer to labelled vials and allow to separate.
Pipette a small amount of solution onto glass slide.
Evaporate water gently on hot plate. Add a small amount of mounting medium (Canada Balsam or Euparal) and allow to warm. Remove and cover with a glass slip.

Tephra were counted on seven transects on the long axis of each slide. A similar method has been used by Bennett et al. (1992), and found to accurately indicate the maximum and minimum concentrations of tephra in the core. Problematic siliceous particles were checked against reference material from Icelandic sediments kindly supplied by Dr Paul Buckland. Care was taken that fragments of opaline phytoliths were not misidentified as tephra (Lascelles, 1993), using phytolith keys (Gilbertson er al., 1991; Powers & Gilbertson, 1987). Examples of the tephras recovered are shown in Figure 2. Figure 3 shows tephra distribution at 10 cm intervals for upper 200 cm. Three zones of tephra concentration were observed, with peaks at 180-190 cm, 50-60 cm and lo-20 cm. These will be referred to as Tephra Kl, K2 and K3 respectively. The detailed analysis of these peaks is described below. As this study concentrates on the environmental impacts associated with these three tephra peaks, palynological and geochemical data are presented from only the top

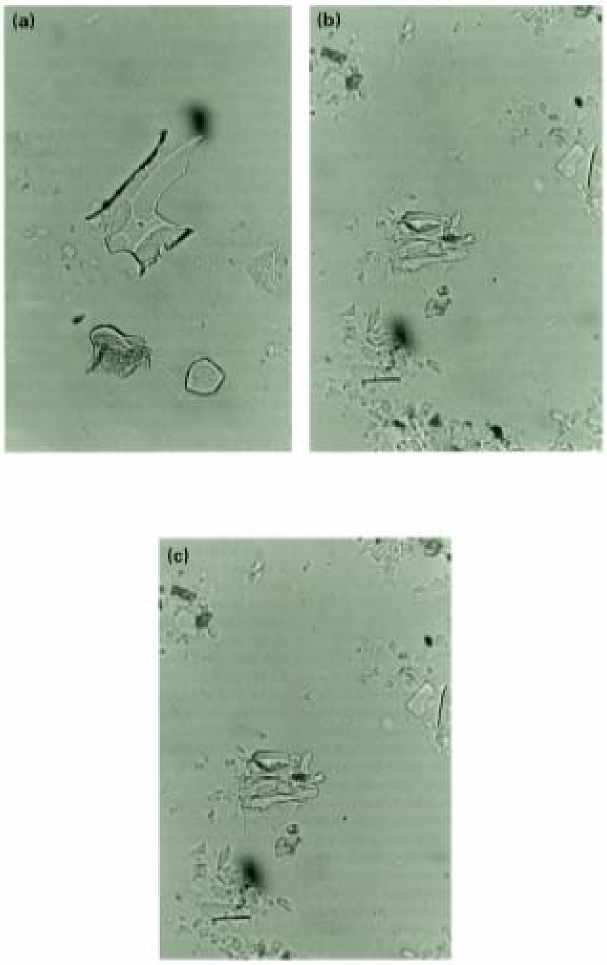

Figure 2. Tephra shards from tephras (a) K1, (b) K2 and (c) K3.

200 cm of the core.

Pollen samples of 1 cm3 were prepared by standard methods (Moore, Webb & Collinson, 1991) and an exotic marker was added (Stockmarr, 1971). Sample spacing was comparable with tephra counts, 10 cm for the top 200 cm and 1 cm within the zones of tephra concentration. Slides were counted at x 400 until a pollen sum of 300 land pollen was achieved. The geochemical impact (if any) of Icelandic volcanic eruptions on the environment of northern Scotland was investigated by a relatively new approach to the analysis of sediment geochemistry, involving the use of a scanning electron microscope fitted with an electron microprobe for energy dispersive X-ray micro-analysis (EDMA). This method is quick and accurate and allows a wide range of elements to be analysed. Data are generated in the form of percentage values, which inevitably limits direct comparisons with the type of information provided by more conventional techniques, such as atomic absorption spectrophotometry, which are typically on fewer elements. As a result of such factors as the variable geometry of the sample face to the X-ray beam, the quantitative accuracy of this procedure on biological samples may be restricted to f 10% relative of the true value (Goldstein et al., 1984; Pyatt & Lacy, 1988) and this has resulted in resistance to its use. However, the technique has recently been demonstrated to be a useful means by which to detect and investigate environmental change (Grattan, 1994; Pyatt et al., in press). Samples of sediment for analysis were extracted from the undisturbed central part of the core by pushing a clean glass tube into the sediment. The tube and sediment were then oven dried overnight, capped and stored. Sediment from each sample was secured on a 13 mm stub using conductive carbon cement and given a light coating of antistatic Duron spray to eliminate the problems caused by electrostatic charges. The samples were analysed on a Jeol-6100 SEM with a Link System eXL X-ray spectrometer using a ZAF-4 program which detected the presence and relative proportion of every element between boron and uranium. For simplicity only a limited range of these elements is presented here. To ensure accuracy, 10 random areas were examined in each case, and three replicates were employed. In the EDMA procedure, an electron beam strikes the solid specimen and a series of interactions occur, including the production of X-rays.

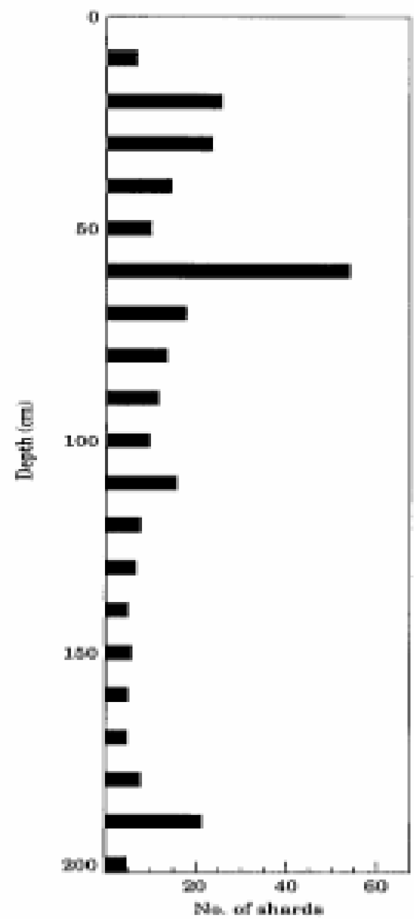

Figure 3. Tephra counts for the upper 200 cm from the Strath of Kildonan.

These are detected by a lithium drifted silicon director and passed on to a multi-channel analyser. Suitable areas for examination on each sample were selected for analysis using the microscope visual display monitor, and analysed at a magnification of 500 x for 100 s of live time at 25 kV (Pyatt & Lacy, 1988).

Palynology and Estimated Tephrochronology

The pollen diagram for the top 200 cm of the core is shown in Figure 4. The aim here is not to describe the complete vegetation history of the area in detail but to provide approximate dates for the tephra peaks iden- (Charman, 1994). Table 1 shows the rationale for the tified, by comparison with the nearest securely dated chronology attached to the pollen diagram. The feapollen diagram from Cross Lochs, 27 km to the north tures dated at the Cross Lochs are paralleled almost exactly at Strath of Kildonan which suggests these are reasonably good regional markers (Table I), although there is good reason to believe that the Cq~MMy~icn rise 1470 f 45 r3r is only a local feature (Charman, 1994). If the derived chronology is accepted as reliable and the tephra peaks are taken to be located at 185 (Kl), 55 (K2) and 15 cm (K3) then their respective dates would be 7650,425O and 880 years BP. However the last of these dates is almost certainly incorrect as it is based on correlation with the CoryluslMyrica rise and extrapolation to the surface assuming a constant peat accumulation rate.

It is therefore not possible to place a reasonable date on K3 by direct comparison of pollen records, but it may be argued that it occurred in relatively recent times as it is so close to the surface. It is tempting to suggest that it may derive from 1783, the “year of the Ashie” (Geikie, 1893) when ash falls and crop damage reputably occurred in Caithness. An alternative view might be that peat cutting has taken place and K3 is therefore much older than this and the sharp boundary between uncompacted surface material to 10 cm and well humified peat below this supports this contention, in which case K3 could date from any time since the early 4th millennium BP onwards. Between the Alms rise at 120 cm (5880 BP) and the Pinus rise at 55 cm (4250 BP) the peat accumulation rate is O-4 mm yr - ‘. The stratigraphy does not change in any major way between 120 and 10 cm and extrapolating upwards from the Pinus rise yields a date of 3250 BP for the K3 tephra. It makes little difference if the Pinus decline is used as a marker, which suggests this estimate is fairly robust. This is remarkably close to the date of Hekla 3 of 1179 BC (calendar). Certainly the earlier date estimate seems more plausible as otherwise peat accumulation would have to have been extremely slow for only 30 cm of peat to accumulate in 3500 years.

The provenance of Kl is unclear, but there are several acid peaks of unknown origin in the Greenland ice-core acidity record (Hammer et al., 1980) and similar tephras identified in nearby Lairg have been tentatively identified as originating in either the Hekla or Ttirfajiikull volcanoes (A. Dugmore, pers. comm.). On the basis of the estimated ages, K2 may be Hekla 4 (Dugmore, 1989). In addition it may be suggested that K3 may be the archaeologically significant Hekla 3, but it may also correspond to similar tephras of as yet unknown provenance identified in Glengarry (A. Dugmore, pers. comm.). Further work on the geochemistry of these tephras will be necessary to explore the specific identity of the tephras properly and this was not possible in this study due to the preparation procedures used. However, the focus of this

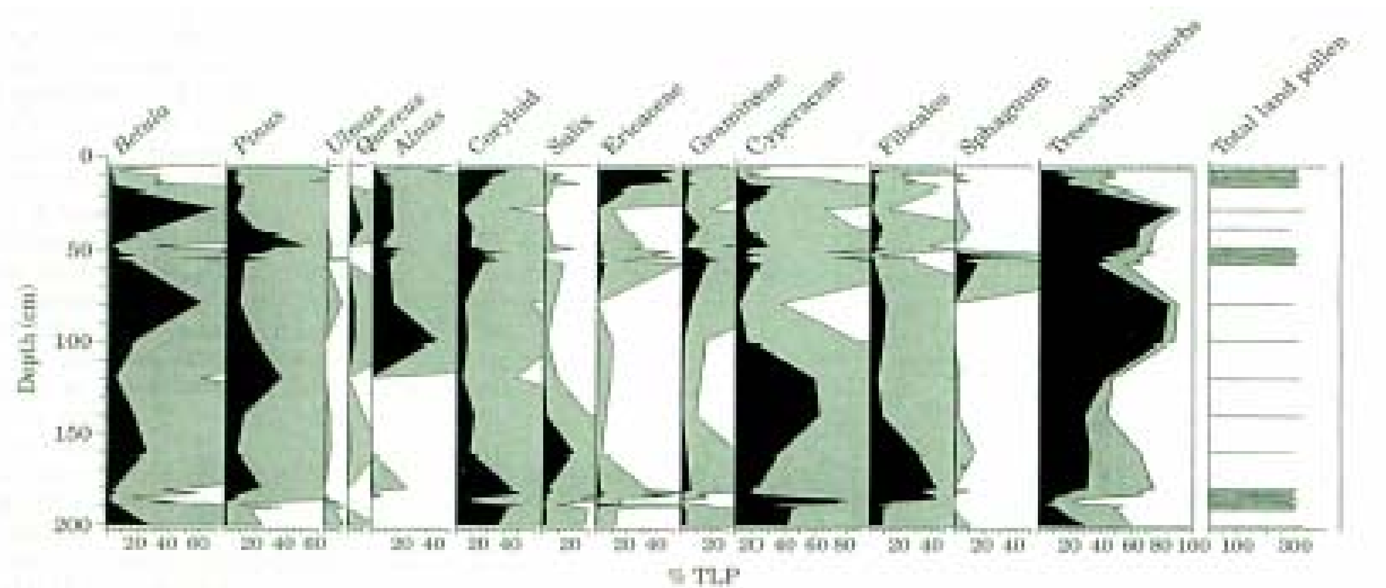

Figure 4. Percentage pollen diagram (% Total Land Pollen) from 0-200 cm for Strath Kildonan. Only species which exceed 5% are shown.

Table 1. Radiocarbon dates (uncalibrated radiocarbon years BP) from the Cross Lochs (Charman, 1994) and equivalent depths in the Strath of Kildonan core

Cross Lochs date (yrs BP)	Horizon dated	Kildonan equivalent depth (cm)
1470 ± 45	*Corylus/Myrica* rise (probably only local)	25
3920 ± 45	*Pinus* decline <20%	45
4250 ± 45	*Pinus* rise >20% (local)	55
5880 ± 45	*Alnus* rise	120
7575 ± 45	*Pinus* rise >10% (long distance)	182
8995 ± 50	*Corylus/Myrica* rise	Below 200

paper is to assess the environmental impact of these three major tephra falls by reference to the palynological and geochemical record. The uncertainty of tephra identity does not undermine this aim.

Tephra Concentrations and Environmental Change

In order to reconstruct the environmental changes associated with the individual tephra falls, the tephra, pollen and geochemistry records at 1 cm intervals are considered together below.

Teplzra KI: 180-l 90 cm c. 7650 BP (Figure 5)

The distribution of tephra is approximately normal and centred on 185 cm. As the tephra fall is assumed to be an instantaneous event, within the relatively compressed timescale of the peat core, this may indicate that there has been subsequent movement of the tephra grains and/or they have been washed into the basin by subsequent surface runoff. The pollen diagram shows two key changes coincident with the tephra. Firstly, there is a decrease in CoryluslMyrica from 40 to less than 10% Total Land Pollen (TLP). Previous levels had not gone below 25% and the subsequent recovery is maintained until 160 cm. Secondly, Cyperaceae increases from c. 30% to >60% over the same interval before declining to c. 10% after the tephra declines. There are also more minor temporary declines in Betula and Ericaceae and Filicales increases to sustained high values. There is a slight increase in the disturbed ground indicators Pteridium and Urtica following the tephra fall. The pollen evidence therefore is for a significant vegetation change coincident with the tephra fall, with a decline in tree and shrub cover and an increase in sedges. There is no obvious stratigraphic change at this time so variability in on-site vegetation is unlikely to account for these changes. Pollen concentration figures also suggest a real decrease in Coryluslu Myrica as well as an increase in Cyperaceae. The influence of the tephra on the sediment geochemistry is clearly demonstrated. The pattern of tephra distribution is paralleled by the geochemistry of Si, K, P and to a lesser extent Ti. Si, K and Ti are all common constituents of tephra grains (Thorarinsson, 1981; Devine et al., 1984; Sigurdsson et al., 1985; Dugmore, 1989). P is less commonly found in tephra, but could derive from basaltic eruptions in eastern Iceland (Jakobsson, 1979). Alternatively, the increase in P may represent a release of nutrients from plant damage and death on the mire itself and within the basin catchment. There is no direct evidence for acidification; Ca does show a decrease but this is continued from much earlier than the tephra fall and must have a different origin. S, Mn and Fe also show no correlation with the tephra fall. The Kl tephra is therefore associated with a significant but temporary change in vegetation. Although the geochemistry clearly reflects the chemical input of the tephra itself there is little evidence for major catchment disturbance from this source.

Tephra k2: SO-60 cm c. 4250 BP (Figure 6)

The tephra distribution during K2 exhibits a clear increase from 55 cm upwards. There is no subsequent decline within the sampled zone and the curve is therefore asymmetric. This may be due to the sampling technique having “missed” the top part of the tephra curve, but the coarse tephra count (Figure 3) shows a similar trend. The tephra distribution illustrates that movement and/or secondary deposition of the tephra

Tephra, geochemistry and selected pollen types diagram for tephra Kl. Pollen is expressed as % TLP, except concentrations which are in grains cm -3. Chemistry is % total elemental composition for elements between boron and uranium. Note different scales for chemistry.in Figure 5. grains may occur following the tephra fall itself, and as deposition may be a significant agent of tephra related a result the identification of the “moment” of deposi- environmental change (Grattan & Charman, 1994), tion is difficult. The clearest trends in the geochemistry this tephra is associated with the highest concentration are of increased Si and K in association with the of S identified throughout the Holocene record of the tephra. As mentioned earlier, this is likely to reflect the core 27.43%. The pollen diagram shows only one chemistry of the tephra itself. Again this suggests that major vegetational change during this period. Pinus the tephra fall has not had a major effect on the rises from c. 15% to 50% at 50 cm depth, returning to catchment stability as reflected in the geochemistry. 10% at 40 cm (Figure 4). This short lived occurrence of But intriguingly, in the light of the suggestion that acid pine has been recognized from across Caithness and eastern Sutherland (Gear & Huntley, 1991; Charman, 1994) and is consistently dated to c. 4000 BP. The reasons for its rapid migration into north east Scotland from further south or its equally rapid decline are not known. Blackford et al. (1992) have suggested that a tephra fall precipitated the decline of the pine via climatic change and/or acidification. Their data from Altnabreac and Loch Leir, only 25 km north of Strath of Kildonan, show a decline from 17 and 15% to 1% and 1.3% TLP coincidental with the Hekla 4 tephra peak and dated to 3700 f 70 BP. However, in the present study, the curves for pine and tephra actually parallel one another and pine rises from 12% to 51%

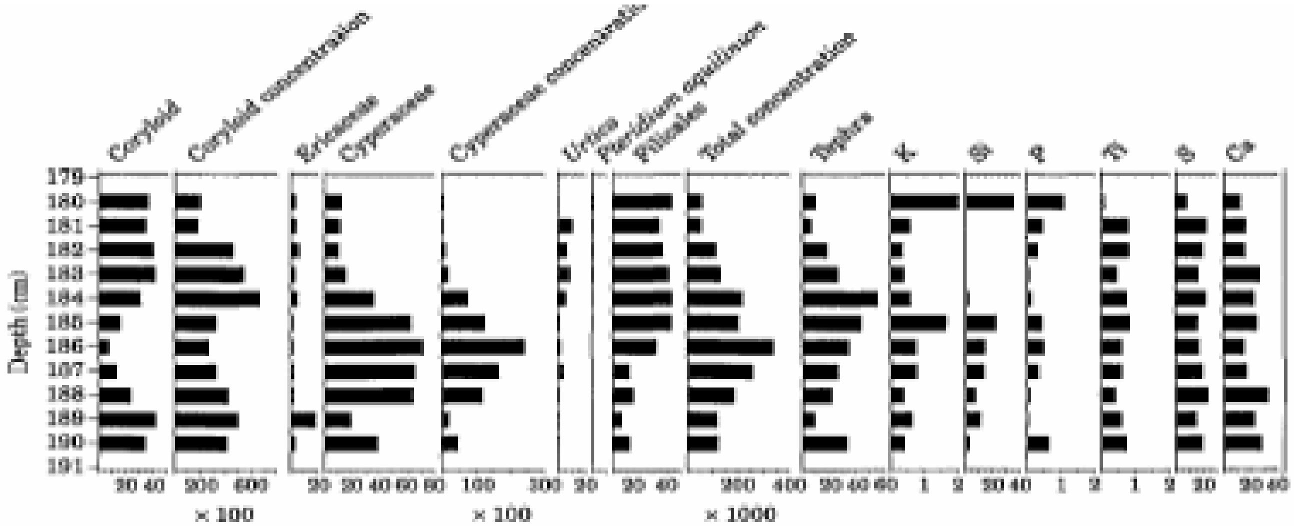

Figure 5. Tephra, geochemistry and selected pollen types diagram for tephra K1. Pollen is expressed as % TLP, except concentrations which are in grains cm^{-3}. Chemistry is % total elemental composition for elements between boron and uranium. Note different scales for chemistry.

over the span of the tephra from 155-150 cm. This suggests that the tephra at Strath Kildonan is associated with the rise of pine rather than its decline in this location.

It is difficult to explain this unexpected result without a more detailed examination of the timing and nature of the change in pine frequencies. It appears that pine spread north at about 4500 BP to cover much of eastern Sutherland and western Caithness (Gear & Huntley, 1991). This may have been in response to drier mire surfaces although there is little direct evidence for this hypothesis. Blackford et al. (1992) suggest that conditions for pine were marginal and the trees were therefore particularly susceptible to the impact of Hekla 4 tephra and suffered severe decline when exposed to this stress. However, the levels of pine pollen at Altnabreac cannot be said to clearly indicate local pine growth-Bennett (1984) suggests that 20% TLP is the minimum acceptable value due to the high productivity and dispersal capability of pine. Certainly at other locations recorded values are much higher; 45% at Loch Strathy (Gear & Huntley, 1991), 48% at Cross Lochs (Char-man, 1994) and 51% (this study). There are no major site differences between Altnabreac, Loch Strathy and Cross Lochs, but the Strath of Kildonan is more sheltered. Furthermore, it could be argued that the date for the decline in high pine values at Altnabreac is quite young: 3700 f 70 compared to a pine peak between 4250 f 45 and 3920 f 45 BP at the Cross Lochs, 4405 to 3815 BP for macrofossil remains and 3930 to 3525 at Loch Strathy. If we accept these arguments then it may be the case that the event recorded at the Strath of Kildonan is not Hekla 4. One of the features of the tephra record for the whole core is that high counts occur for the whole of the top 100 cm, although we have identified the two major peaks. There may be other eruptions recorded here which more detailed sampling would reveal more clearly; Hekla 4 may be one of these. Clearly while dating is problematic, it seems possible that the pine decline recorded by Blackford et al. (1992) is a secondary decline, perhaps the same event recorded at Cross Lochs c. 20 cm above the major pine decline (Charman, 1994). Since the diagrams of Blackford et al. (1992) cover only 6.5 cm of peat from a similar depth to the Cross Lochs profile, this remains a clear possibility.

There are therefore two possible interpretations of the new evidence presented here. (1) The K2 tephra is a tephra older than that of Hekla 4, where the impact does not appear to have been significant enough to inhibit the expansion of pine. (2) Hekla 4 is represented by the K2 tephra and the differences in levels of pine pollen are attributable to local differences in vegetation patterns. If this is the case then our evidence suggests that Hekla 4 was not associated with the more widespread pine decline in the whole of this area (cf. Hall et al., 1994) and that pine was able to grow unhindered in more sheltered sites with better drained soils. There may also have been some differences in the fall-out pattern of the Hekla 4 tephra. Given the uncertainties over the dates ascribed to K2 and the clear potential for there being additional tephras in the top 100 cm of

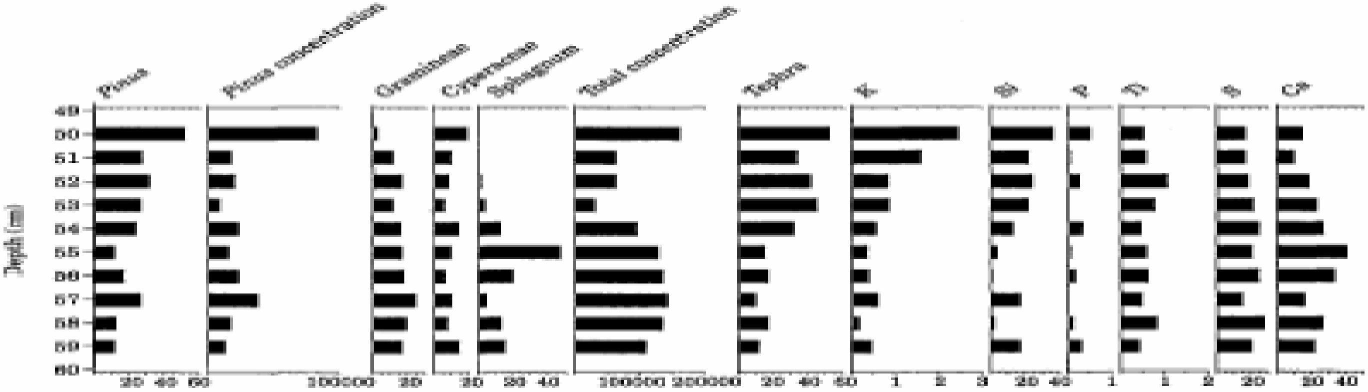

Figure 6. Tephra, geochemistry and selected pollen types diagram for tephra K2. Note different scales for chemistry. Scales same as in Figure 5.

peat (possibly including Hekla 4), the first explanation seems more likely. However, the fact that a significant tephra fall such as K2 is associated with the pine rise does suggest that we should be careful in identifying the Hekla 4 tephra fall as the main mechanism for the widespread pine decline at a later date. It seems unlikely that pine could expand into marginal habitats whilst suffering the impacts of one tephra fall and then be decimated by a later volcanic event.

Whether K2 is Hekla 4 or not, the arguments above suggest that the primary cause of the major pine decline remains enigmatic, but it is more likely to be the result of previously suggested factors of progressive climatic deterioration and increasing soil moisture, perhaps augmented by anthropogenic disturbance. This is an area which clearly requires more work determining the spatial and temporal variability of Pinus records and tephra falls in north east Scotland for this period to finally resolve this issue.

Tephra K3: lo-20 cm c. 3250 BP? (Figure 7)

The pattern of tephra distribution in the top part of the core is not as clear as the earlier events. Counts are low at 20 cm and rise to very high values between 18 and 14 cm before declining but maintaining significant levels until the end of the sampling zone. Again this indicates tephra movement subsequent to deposition. In this case it may be intensified by surface disturbance, particularly if peat cutting has taken place, which would cause major disruption to the top of the profile. Any interpretation of the record must bear this in mind. The top part of the core (Figure 4) shows a major vegetation change between 30 and 20 cm with a decline in birch and an increase in CoryluslMyrica and Ericaceae. However, this change is established well before the tephra rise which does not begin until 19 cm depth. In fact it is coincident with more intense human activity as indicated in the pollen record by Plantago lanceolata and Urtica. During the period of high tephra counts, the pollen record shows no major fluctuations. There is thus no evidence in the pollen record for major environmental impact of the tephra fall. The geochemistry again reflects the presence of the tephra in increased Si and K. This is also shown by Al. While the record is likely to be somewhat disturbed during K3, the pollen and geochemical evidence do not suggest any significant environmental change that is clearly associated with the tephra fall. The effects of anthropogenic disturbance are evident and this may also serve to obscure the impact of the tephra. This is unfortunate as it has already been suggested that this may be the archaeologically important Hekla 3 eruption. If this is the case, then the sheer amount of tephra does support the contention that this eruption did result in a comparatively massive deposition of volcanic material in northern Scotland, although there is no evidence here for significant environmental change. The investigation of further sites with more complete recent records will be necessary to test the hypotheses of Burgess (1989) using palaeoenvironmental techniques.

Discussion and Conclusions

The results described above show that there have been at least three major volcanic events which have resulted in significant tephra deposition in north east Scotland during the Holocene. There may be further events which remain undetected in this study due to the likely truncation of the record in the top part of the core and the possibility of additional discrete tephra peaks in the surface metre of peat. The events recorded are tentatively dated to 7650, 4250 and 3250 BP and it seems most likely that these may be HekWTiirfajdkull, Hekla 4 or an eruption immediately predating it, and perhaps Hekla 3. However, whether the specific identities of the eruptions are correct or not, there are a number of important conclusions from this work, pertinent to other studies and future work. There are major variations in the magnitude of each of the events and the associated environmental changes. The initial investigation of 10 cm wide scrapes suggested that K2 was the largest event followed by K3 and Kl, but detailed analysis showed that Kl and K2 contain approximately the same amount of tephra while K3 peaks at twice the original estimate. There may also be other smaller events elsewhere in the core.

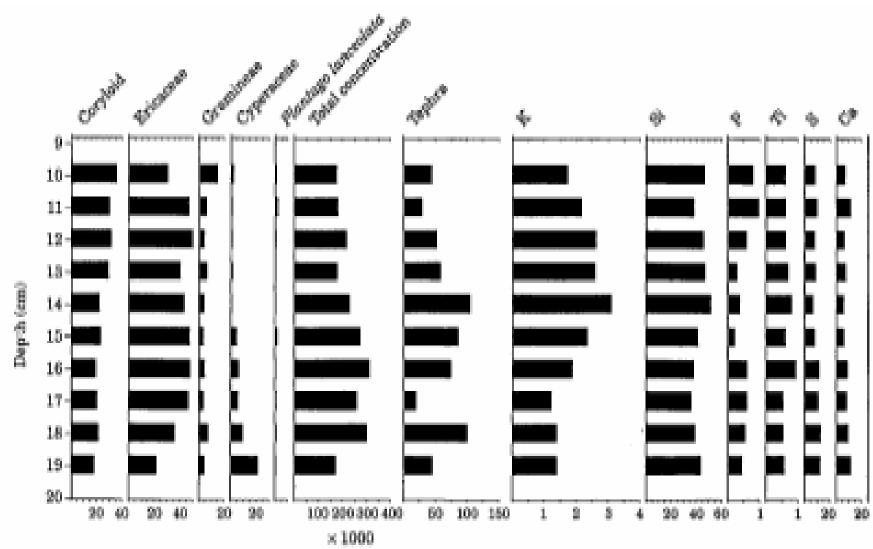

Figure 7. Tephra, geochemistry and selected pollen types diagram for tephra K3. Note different scales for chemistry. Scales same as in Figure 5.

When the evidence for associated environmental change is assessed only the Kl and K2 tephras are associated with evidence for significant vegetational change, and in each case the nature of the change is different. If the vegetation changes and the geochemistry and tephra fall are causally related, then this work demonstrates that the impact of volcanic deposition distant from source is very variable and, therefore difficult to predict with any certainty. Furthermore, the absolute quantity of tephra is not necessarily directly proportional to the environmental impact. The relationship between pine history and tephra falls in north east Scotland is clearly more complex than was originally envisaged (Blackford et al., 1992). The positive association between the K2 tephra and pine pollen reported here is opposite to the relationship between the Hekla 4 tephra and pine pollen reported from Altnabreac. While we can identify such relationships in the palaeoecological record, cause and effect should not be ascribed in the absence of additional supporting data. As further tephra are identified in northern Britain, the potential for discovering associated vegetation and catchment changes becomes proportionally greater. A highly critical, cautious approach needs to be adopted in assessing the extent to which the events are causally linked.

The redistribution of tephra within the profile causes difficulty with estimating the timing of individual events. Solving this problem is critical if the difficulties over ascribing cause and effect are to be better resolved. High resolution pollen analysis of peats assumes there has been negligible movement of pollen grains but the work of Butler (1992) suggests that there may be considerable vertical displacement in peat and other sediments. It is certain that each event would not last for more than a year or two at most, yet tephra can be distributed over a depth of at least 7-8 cm (c. 150 years) of peat and it is perhaps unreasonable to expect that reworked tephra was being deposited in a mire so long after the initial impact. The same spread of material is reported from raised mires in northern Ireland (Pilcher & Hall, 1992) and these authors have suggested that pollen must undergo similar kinds of post depositional movement. This may be by the limited amount of bioturbation possible in acidic mires or by gravitational and hydrological effects. In this case one would expect there to be more downward than upward movement-a pattern clearly shown in IQ. Another mechanism which could explain the widespread distribution of tephra in the profile is inwash from the surrounding slopes. This is more likely in basin mires and, to a lesser extent in sloping blanket mire, than in raised mires where it is impossible.

Further examination of silica particles determined as non-tephra, showed some were identifiable as phytoliths (Powers & Gilbertson, 1987; Powers, Padmore & Gilbertson, 1989). Other fragments were abraded and damaged silica similar in size to tephra grains. When compared with the original tephra counts, counts of these “damaged tephra” showed a clear correlation. Although these data should be viewed with caution, they provide further evidence that inwash from surrounding slopes may have been significant.

Finally, it was hoped that EDMA for geochemistry would provide useful indications of environmental changes associated with tephra deposition, such as acidification and erosional episodes. There is little unequivocal evidence for either of these impacts in the geochemistry, primarily because of the influence of tephra geochemistry on the total geochemical signature, but also due to the long. term trends in the sediment record which are difficult to separate from tephra induced changes if indeed these exist. However, the technique is promising for the detection of environmental changes and deserves further development.

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